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The Role of Deep Convection and Strong Winds Aloft In Triggering Gales Over the Persian Gulf: Comparative Case Studies

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ABSTRACT—A situation that led to rapid development of strong winds over the Northern Persian Gulf is compared with a similar situation in which gales were anticipated but did not occur. In both cases, cold air accumulated over Syria and Northern Iraq. In the first case, deep moist convection over the mountains of Northwestern Iran was coupled with a rapid southwest surge of a tongue of cold air into the Persian Gulf. In the second case, deep convection did not occur, and the cold air did not move southward. Release of latent heat by deep convection and merging of the rising currents with strong winds aloft seemed to have reinforced upslope winds near the surface in the first case, which lifted the warm air in front of the advancing cold air. This explanation is made plausible by a simple energy budget.

1. INTRODUCTION

Winds of more than 30 kt are uncommon over the Persian Gulf; when they do occur, they rarely last longer than a few hours. This happens from time to time during the winter months, when they are almost entirely associated with a surge of cold air from the Mediterranean and Black Seas following the passage of cyclones. During late summer and early autumn, northwesterly winds above 15 kt are rare, and the frequency of winds over 25 kt across the northern part of the gulf is virtually zero. Figure 1 shows the topography of the area.

On Sept. 12, 1969, a blinding sandstorm with sustained winds greater than 35 kt occurred over open water near Kharg Island in the northern Persian Gulf. The wind generated 8-ft waves, which caused damage and delay to pipe-laying operations in the area. The development of this storm was difficult to follow on the conventional surface and upper air analyses but could be traced back after careful three-dimensional analysis of the temperature distribution and the flow. Time-to-space conversion was successfully applied in this analysis. Maps of potential temperature distribution also provided a better insight into the behavior of the flow over mountainous terrain. To delineate the areas above which orographic lifting could be expected, we computed terrain-induced vertical velocities from the slope of the terrain and its orientation with respect to the flow near the surface.

On September 15, a surge of cold air moved eastward over the eastern Mediterranean. By the 16th, a low-level vortex developed ahead of the cold air with fairly strong winds over Iraq. At this time, the meteorological services predicted a strong northwester over the Persian Gulf; during the following days, however, the wind speed remained below 15 kt.

Comparative case studies of these intrusions suggested that the southward thrust of colder air toward the Persian Gulf on September 11 was controlled by deep convection over the mountains of Iran in combination with strong winds aloft.

2. CASE STUDY OF SEPTEMBER 10–12, 1969

At the beginning of this period, polar continental air was being swept southward into the Middle East under the influence of a large, intensifying cold anticyclone over Russia. This anticyclone moved toward the southeast with its central pressure increasing from 1024 mb on September 9 to 1032 mb on September 11. Some of this subsiding air, which was piled up over the Black Sea, escaped via the Bosporus and the Aegean Sea; as the anticyclone continued, considerable amounts spilled over the lower elevations of Turkey into Syria and Northern Iraq. Nimbus 3 high-resolution infrared radiometer HRIR daytime cloud photographs show that this intrusion was preceded by deep convection. Dust storms and thunderstorms were reported at the surface near the Turkish-Syrian border and over Northern Iraq.

The surface and upper air analyses at 1200 GMT on September 11 are displayed on the left side of figures 2–5. Figure 5B shows the distribution of the depth of the cold air. Weak winds in the cold dome during the morning hours of the 11th gave no clear indication of the location of its slowly moving forward edge. In the afternoon, however, it suddenly surged as a narrow tongue toward the Persian Gulf. This surge is vividly displayed both on the potential temperature map (fig. 2B) and by a low-level wind maximum in the time-height section of the vertical wind profile at Baghdad, Iraq (not shown). Particularly

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noteworthy as precursors of the intrusion of polar air were the strong upslope winds over the mountains of western Iran and the band of strong upper level westerlies over the plateau to the east (figs. 3A, 3C). Patterns of terrain-induced vertical velocities near the surface (fig. 4A) and large areas of convective clouds over the northern half of Iran indicate that the warm air ahead of the cold tongue was lifted, opening a path for the cold outflow toward the Persian Gulf. Release of latent heat by convection and the merging of the rising currents with a band of 50- to 60-kt winds above 500 mb may have accelerated this process. Once the cool air arrived over the warm waters of the gulf (air temperature 32°C, sea temperature 33.5°C), the boundary layer became unstable and surface winds along the front rapidly became gusty and increased to an average of 35 kt due to transfer of momentum from the upper part of the boundary layer, where a wind velocity maximum had existed earlier.

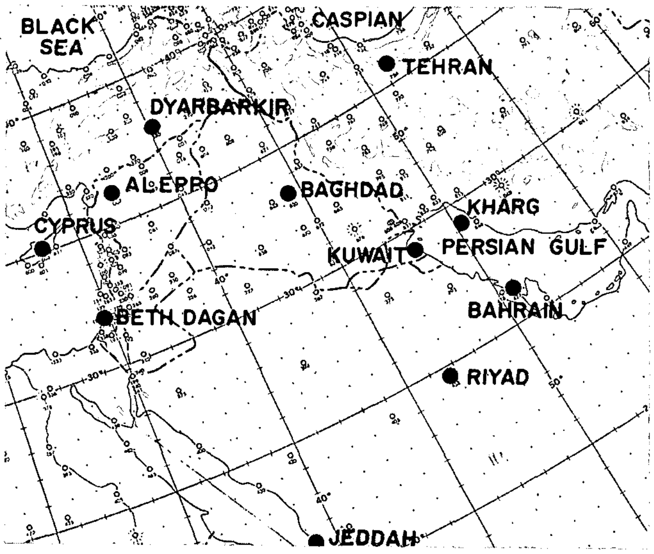

FIGURE 1.—Topography of the Middle East and location of the pertinent meteorological stations.

3. CASE STUDY OF SEPTEMBER 15-17, 1969

A fresh incursion of cool air into Syria on September 15 and 16 came from the west rather than from the north. Otherwise, the temperature patterns were remarkably similar to those on the 11th with fairly deep, cold air over Syria. The unexpected development of a mesoscale low-level vortex over Iraq was induced by a small cold Low at 500 mb, which could not be detected and tracked other than by careful time-to-space conversion of the wind patterns in the time-height sections for Beth Dagan and Baghdad. After the appearance of the vortex on the surface maps, strong northerly flow at its rear was predicted for the upper Persian Gulf. As a result of pressure rises over the eastern Mediterranean, however, most of the cold air was siphoned into the Red Sea; the remainder flowed northeastward leaving none of the cold air to reach the Persian Gulf. Hence, the winds remained weak over that area. Further description of this case study is in the form of a comparison with that of September 11, and reference is made to the right side of figures 2–5.

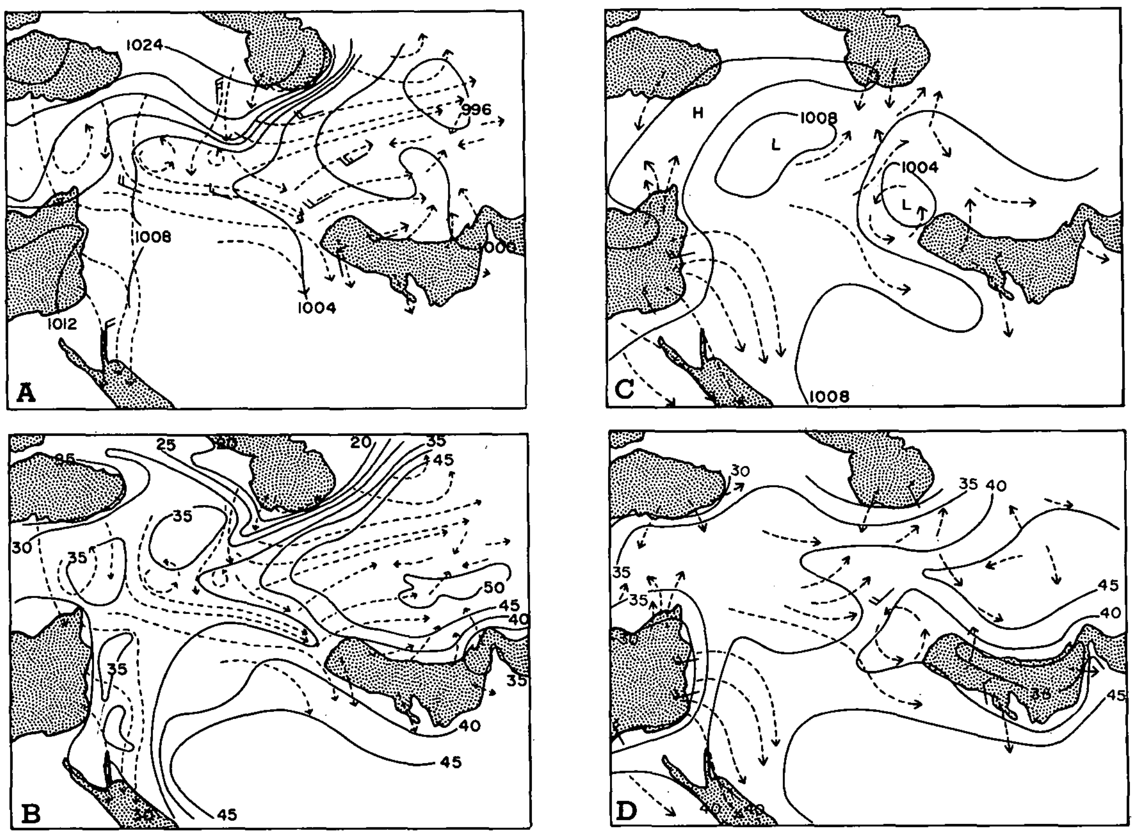

FIGURE 2.—(A) surface pressure (mb) and (B) potential temperature (°C) at 1200 GMT, Sept. 11, 1969; (C) and (D) same as (A) and (B), respectively, for Sept. 17, 1969. Wind flow is given by dashed lines on all charts. Note that the maps are two-dimensional but the flow is three-dimensional.

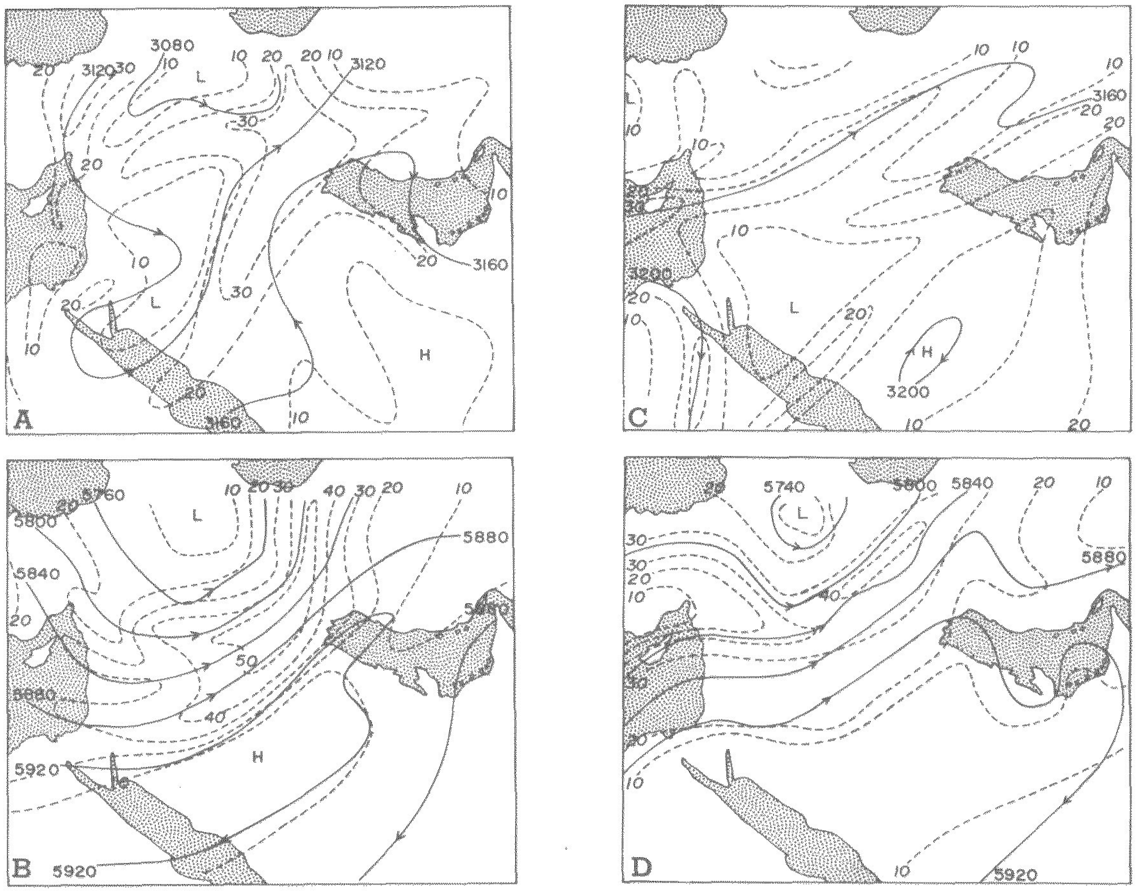

FIGURE 3.—Potential temperatures (°C, dashed lines) and flow (solid lines) at (A) 700 mb and (B) 500 mb for 1200 GMT, Sept. 11, 1969, and (C) 700 mb and (D) 500 mb for 1200 GMT, Sept. 17, 1969.

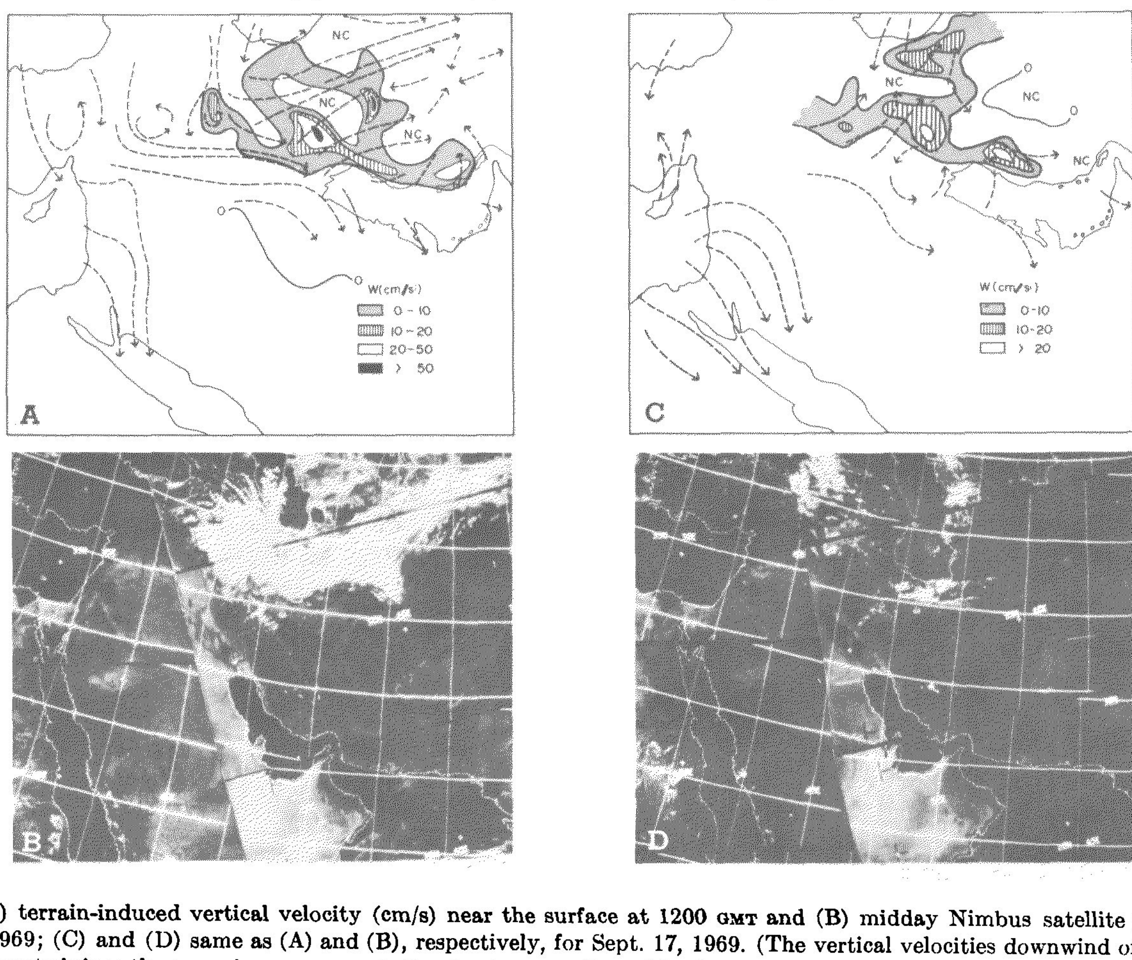

FIGURE 4.—(A) terrain-induced vertical velocity (cm/s) near the surface at 1200 GMT and (B) midday Nimbus satellite photographs on Sept. 11, 1969; (C) and (D) same as (A) and (B), respectively, for Sept. 17, 1969. (The vertical velocities downwind of the mountains are not computed since they may be unrepresentative due to separation of flow).

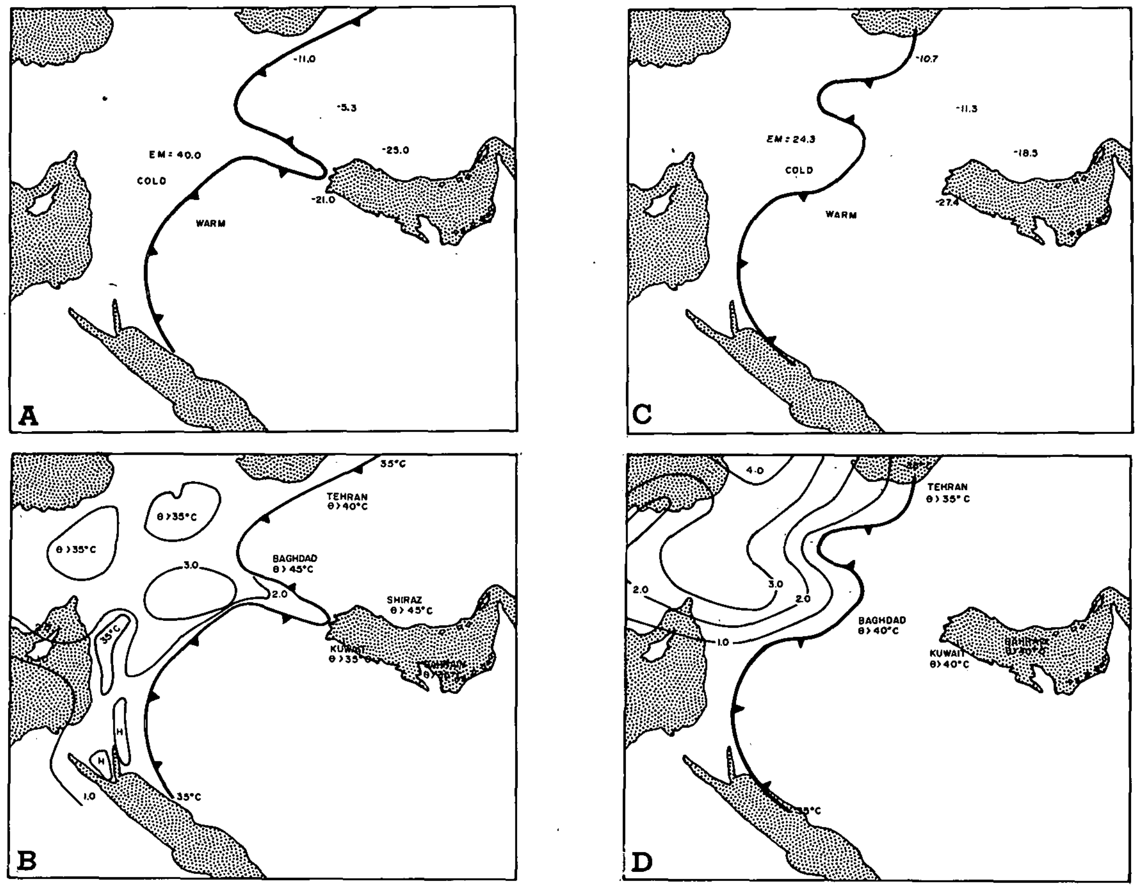

FIGURE 5.—(A) comparison of the Margules energy index, E_M, with the energy needed to lift a 200-mb deep layer over a pressure interval of 500 mb and (B) depth (km) of the cold air at 1200 GMT on Sept. 11, 1969; (C) and (D) same as (A) and (B), respectively, for Sept. 17, 1969

First, the initial surface flow pattern was much more organized on September 10 and 11 than on September 16 and 17. In fact, the low-level vortex over Iraq on the 16th blocked rather than enhanced cold inflow into the Persian Gulf. By the time it moved away, the cold air had been subjected to modification by surface heating sufficiently long to lose its temperature contrast with the warm air. The flow at 700 and 500 mb was also better organized and stronger on the 11th than on the 16th and 17th. After the decay of the 500-mb Low over Iran on the 17th, when the flow pattern became more simplified, the 500-mb wind maximum shifted farther north toward the Caucasus mountains. This diminished the chances of reinforcement of any convective currents over the mountains north of the Persian Gulf. Due to lack of organized surface flow perpendicular to the mountain ridges, terrain-induced vertical velocities were weaker (fig. 4C) and deep moist convection was virtually nonexistent (fig. 5D). The afternoon soundings over Iraq and Iran indicated lack of moisture for this convection.

4. ENERGY CONSIDERATIONS

Inspection of the sounding of September 11 at Kuwait suggests that lifting of the warm air near the Persian Gulf over a pressure interval corresponding to the height of the mountain range would result in sustained moist convection. The sounding of September 17 did not show this possibility (fig. 6). Since the shaded positive area on the T-log p diagram is a measure of energy, its use for a simple energy budget is considered here. Secondly, lifting of the warm air to its level of free convection would have to be accomplished by the penetration of cold air underneath.

Once moist convection is established, its kinetic energy can drive the circulation that pumps warm surface air into bands of strong winds aloft. The two other contributing energies that suggest themselves are the conversion of potential energy into kinetic energy by the rearrangement of cold and warm air along the surface of the discontinuity between the two and, second, the work that has to be done against the negative buoyancy of the conditionally stable air below a level of free convection or any other specified level. Margules has provided a simple energy index that results from his theory of dry-adiabatic rearrangement of two adjacent air masses with different potential temperatures (Hess 1959, pp 297–302). This energy is given by

$$E_M=\frac{1}{2}mC^2=\frac{1}{8}mgh\left(\frac{\Delta T}{\overline{T}}\right) \tag{1}$$

where m is the mass, C is the wind speed, g is gravity, h is the initial height of the column of cold air, and ΔT is the difference of average absolute temperatures, $\overline{T}$. (Note that in reality the temperature lapse rate in the cold air is dry

TABLE 1.—*Comparison of* E_M *and* E_B *at Kuwait for 1200* GMT *on Sept. 11 and 17, 1969*

Date	E_M	$E_B(300)$	$E_B(700)$
Sept. 11	10.0	−3.7	33.0
Sept. 17	6.1	−1.4	−34.4

adiabatic over the strongly heated desert.) To this source of energy, one has to add an unknown amount of energy dissipated by friction, E_F. The other energy, E_B, is the work done to lift a column of conditionally stable warm air of height H over a height interval that is at least equal to that between the surface and the level of free convection. E_B (300) and E_B (700) are computed for a 50-mb deep layer, which is given a lift over pressure intervals of 300 and 700 mb, respectively. Units are in $m^2 \cdot s^{-2}$. E_B is compared with E_M for the corresponding depth ($h=500$ m) of the cold air.

Per unit mass, this energy is expressed as

$$E_B=\frac{1}{n}\sum_{0}^{n}\int_{p_b-n\Delta p}^{p_t-n\Delta p}\frac{\Delta T}{\rho T}\,dp=\frac{R}{n}\sum_{0}^{n}\int_{p_b-n\Delta p}^{p_t-n\Delta p}\frac{\Delta T}{p}\,dp \quad (2)$$

where T is a function of p and R is the gas constant. p_t and p_b are the pressures at the top and the bottom of the column and n is the number of equal pressure intervals over which the summation takes place. The energy index, E_B, can be evaluated rapidly on a real-time basis with the aid of a desk calculator.

The energy equation [eq (1)] can now be written for a unit mass in the form

$$E=E_M+E_B$$

or

$$E=E_M-(E_F-E_B). \quad (3)$$

If E_F-E_B is positive and larger than E_M, the advancement of the cold air will be halted. However, the dissipation of energy by friction, E_F, which is a function of wind speed, depends on E_M and E_B as well as on the terrain and is difficult to estimate. Also, Margules' model is strictly a closed system. Import and export of kinetic energy are difficult to evaluate with insufficient data. Hence, we can only show here that E_M was larger in the case of September 11 than in the case of September 17 (table 1).

From the soundings in figure 6, we first computed E_B for the layer between 1000 and 950 mb. The corresponding depth, h, for the computation of E_M is 500 m. Lifting this layer over a depth of 300 mb (to its level of free convection) required a relatively large amount of energy on the 11th; however, since there was deep convection on that day, a lift over a pressure interval of 700 mb was more likely, and this results in a large positive value of E_B. The air on the 17th was too dry for moist convection; hence, E_B remained negative and decreased with the amount of lift. The comparison between the two cases suggests the feasibility of the above indices as a forecasting tool, perhaps with the speed of the upper tropospheric wind as a third independent variable. Reinforcement of updrafts by strong winds aloft has been mentioned

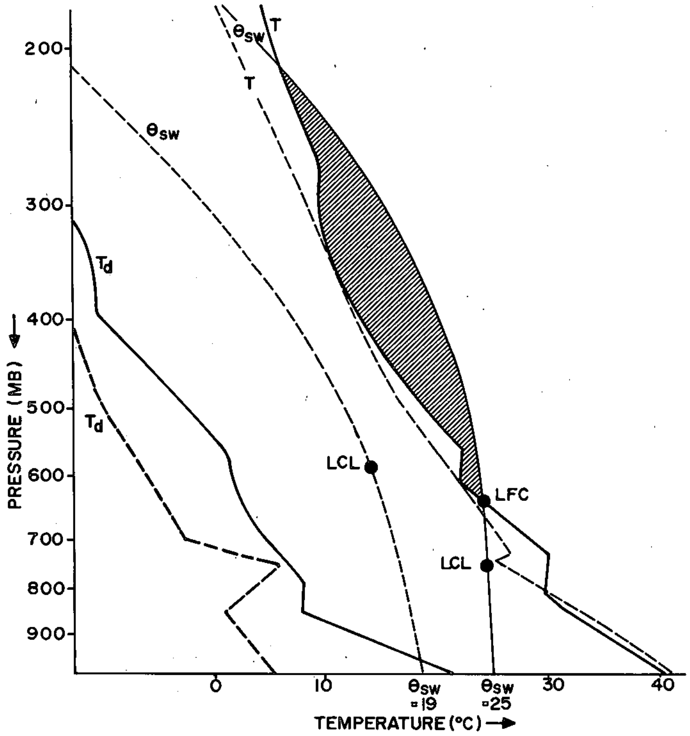

FIGURE 6.—Afternoon soundings at Kuwait for Sept. 11 (solid lines), and Sept. 17, 1969 (dashed lines). The shaded area represents the energy released by latent heat of condensation for moist-adiabatic ascent.

by Dessens (1960) and Cunningham (1960); so far, however, no attempts have been made to describe its mechanism or to compute its magnitude. Significant upper level divergence, which would strengthen the updrafts, is not necessarily always present prior to the onset of deep convection but rather seems to result from it (Ninomiya 1971). These findings emphasize the need for refinement of the proposed theory and its substantiation by more and better observations. Without drastic improvement in the availability and quality of meteorological data in the Persian Gulf area, however, further modification of the simple energy considerations will neither substantially change the kind of results presented above nor enlarge their scope. Hence, simple combinations of the wind speed near 300 mb and kinetic energies derived from differences in potential temperature between air masses, and indices of the energy required for lifting the warm air above the level of free convection and the energy released by latent heat during subsequent ascent, should be tested as forecasting tools.

5. CONCLUSION

Comparison of a situation leading to gale winds over the Persian Gulf with a similar situation not associated with strong winds suggests that subsynoptic scale disturbances can, to a large extent, control intrusions of unstable polar air over the warm sea. Three-dimensional analysis will reveal the structure of these disturbances. However, the paucity of surface and upper air data over the Middle East makes it mandatory to use time-height sections and careful time-to-space conversion for the detection and tracking of these small systems, taking into account possible individual changes. Masking of temperature differences on the surface maps by topography can be overcome by plotting potential temperatures rather than actual temperatures.

Although the area is nearly void of clouds, satellite observations sometimes indicate areas of moist deep convection over high terrain. Latent heat released by this convection and the merging of the updrafts with strong winds aloft may be powerful as mechanisms that reinforce upslope winds. These in turn remove the warm air and free the way for intrusions of polar air at lower elevations, thus accelerating their southward movement. Combinations of simple concepts like Margules' index for the conversion of potential energy to kinetic energy and a buoyancy index for work done against gravity and energy released by condensation of water vapor may help where other forecasting tools cannot be found.

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